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METHODS FOR ACHIEVING TV SIGNAL DELAY USING ULTRASONIC WAVES

I. V. Zakharov

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METHODS FOR ACHIEVING TV SIGNAL DELAY USING ULTRASONIC WAVES /29

I. V. Zakharov

Methods are considered for delaying television signals for a period of a few lines or frames. A survey is made of ultrasonic delay lines for large delay periods.

Electric delay lines are successfully used for delaying the television signal by short intervals of time (a part of one line). In some cases it is necessary to produce the delay for prolonged intervals of time. In the SECAM color television system the horizontal and vertical definition of the color image is made approximately equal by producing the signal of one line twice which requires a delay of the signal in the receiver for a period of one line (40 μsec). This is necessary because the corresponding definitions along the horizontal line are decreased due to the smaller bandwidth of the color signals compared with the bandwidth of the intensity signal (Ref. 1). In some systems the volume of the television signal must be delayed for a period of time from one line to several frames (Ref. 2). By delaying the signal it is possible to increase the immunity to noise, and in this case high correlation of the television signal is used. For example, the signals of adjoining frames differ little from each other and the noise is statistically independent. In summation the signals are added algebraically while the noise follows the mean square law. By using the relation between the signals of two lines it is possible to increase the signal/noise ratio to at least 3 db.

The following methods may be used to obtain a large time delay: 1) magnetic recording and subsequent reproduction; 2) use of electron storage tubes; and 3) use of ultrasonic delay lines (e.g., those used in the SECAM system).

The delay interval must vary in correspondence to the frequency of the lines and preferably in an automatic manner.

The following effects occur in ultrasonic delay lines: 1) electric or magnetic oscillations are transformed into ultrasonic oscillations; 2) ultrasonic oscillations are propagated in a solid body or in a liquid; and 3) ultrasonic oscillations are transformed into electric or magnetic oscillations.

Since the propagation of ultrasonic waves in the transmitting medium is slower compared with the velocity of light, the ultrasonic delay line (for the same delay time τ_d) is much shorter than an electric delay line. It is for this reason that the realization of large τ_d depends on the

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exclusive use of ultrasonic lines. Specially constructed cables make it possible to decrease the length of the line (Table 1). In cable PK-3 a delay by one meter corresponds to T = 0.7 μsec/meter. The length of the cable necessary to produce a delay by one line is given by the equation:

$$l = \frac{64}{0.7} = 91.5 \text{ meters.}$$

Table 1.

Type of cable	RG-65/U	HH-1500	DL-1100	HH-2500	HH-4000	HH-1600
Delay time for 1 meter (μsec/meter)	0.14	0.23	1.8	2.0	3.35	3.35

One of the experimental lines has a delay time T = 30 μsec/meter. Then l = 2.15 meters. Due to reflections, considerable distortions occurred in this line.

In all electric delay lines attenuation increases with frequency (for 10 megacycles b = 6db/μsec). Phase distortions increase above 1 Mc. For τ_d = 40 μsec the rise time is 4 to 16 μsec which is entirely unsuitable.

Ultrasonic Waves

Only longitudinal waves (L-waves) are propagated in liquids with a velocity $C_L = (\rho B_{adiabatic})^{-1/2}$, where ρ is the density, $B_{adiabatic}$ is /30 the coefficient of adiabatic compressibility.

The velocity of L-waves in solid bodies is equal to: $C_L = (E/\rho)^{1/2}$ where E is Young's Modulus.

Transverse oscillations take place in solid bodies. In a particular case the displacements are exactly perpendicular to the direction of propagation (S-waves). The velocity of the S-waves is given by the equation:

$$C_s = (G/\rho)^{1/2}$$

where G is the shear modulus.

Cylindrical rods will also support flexural oscillations and torsional oscillations (T-waves).

If the wavelength Λ is greater than the diameter of the rod then the velocities of longitudinal and torsional oscillations do not depend on Λ. The velocity of T-waves is equal to $C_T = (\mu/\rho)^{1/2}$ where μ is Lamay's coefficient of rigidity. The velocity of flexural waves depends on Λ: $C_F = 2\pi C_L k/\Lambda$, where k is the radius of inertia of the cross section for very short waves. As the length is decreased waves C_F and C_L approach the velocity of Rayleigh waves (C_S). For oscillations of the basic type the velocity of torsional oscillations does not depend on frequency. The lower velocity of S-waves is responsible for their preferred application in the case of very large delays. The dispersion, i.e., the dependence of the velocity of ultrasonic oscillations on frequency, results in different delays at different frequencies.

Transducers

The direct and inverse piezoelectric effect is used to transform electric oscillations into ultrasonic oscillations and to transform ultrasonic oscillations into electric oscillations. Most frequently, quartz transducers are used which resonate at $t = \frac{\Lambda}{2}$ (t is the thickness of the transducer), i.e., $f = \frac{k \cdot 10^6}{t(mm)}$. According to experimental data k = 2.87 for quartz, 1.4 for Rochelle salt and 2.0 barium titanate. The transducer may operate at its harmonic frequencies, and frequencies of 50-100 Mc have been obtained. Crystals of $BaTiO_3$ (Ref. 3) are used to excite and receive shear waves. These transducers have lower losses compared with quartz transducers (20 db instead of 40 db). Their bandpass is wider ($\frac{\Delta f}{f}$ = 0.4 and 0.3 for quartz). The coefficient of electromechanical coupling is greater by a factor of 4.6. Unlike other synthetic piezoelectric materials, barium titanate is inexpensive to manufacture. Practical applications have been made of alloys of barium titanate, lead titanate, and calcium titanate. To obtain high powers it is necessary to apply a high voltage to a piezoelectric radiator. The power is proportional to the area of the plate of the radiator. Therefore, at high frequencies the delivered power decreases. Since one side of the radiator is usually not loaded, the operation at harmonic frequencies is usually associated with the excitation of odd harmonies.

Magnetostrictive Transducers

The transformation of magnetic oscillations into ultrasonic oscillations as well as the inverse transformation of the ultrasonic waves into magnetic waves is based on the direct magnetostrictive effects in which the variation of the magnetic flux produces the following: 1) longitudinal oscillations, 2) flexural oscillations; 3) torsional oscillations; and 4) changes in volume. The inverse magnetostrictive effects include the following: 1) longitudinal and transverse; 2) torsional; and 3) volumetric. Most frequently the direct and inverse longitudinal effect is used. The stress is two orders of magnitude lower than for the case of piezoelectric transducers; however, a large amount of power can be delivered. The principal losses in magnetostrictive delay lines are due to the mismatch between the vibrator and the medium (Ref. 10).

The length of the rod vibrator is given by the equation: $l = \frac{n}{2f} C_L$,

where n is the order of the harmonic. For a ring vibrator $f = \frac{C_L}{2\pi r}$

$\sqrt{1 + (1 - n)^2}$, where r is the radius of the ring.

Rod vibrators are used exclusively to excite frequencies above 100 kc. It follows from elementary theory that operation on harmonic frequencies is possible, but this is not true at high frequencies when the influence of dispersion inductance increases. The effective length of the transducer is increased compared with its geometric length and the point of maximum power transfer is displaced into the region of higher frequencies while the power transfer at harmonic frequencies decreases sharply. Thus, the power transfer at the second harmonic drops by a factor of 15-20 (at lower frequencies the power transfer at the second harmonic is smaller by a factor of 4). The efficiency of the transducer is increased by decreasing the dispersion inductance, and this is achieved by decreasing the number of turns and magnetically shielding the transducer, etc. Frequencies up to 1.5-3.0 Mc have been obtained (Ref. 4). /31

Since the rod which is made from magnetostrictive material gets longer (or shorter) during any increase in the magnetic induction, the change in direction of induction (a change in the direction of the current in the winding) again leads to an increase (or decrease) in the length of the rod. As a result of this, the signal is differentiated.

To avoid differentiation the receiving transducer is magnetized with a constant magnet while the transmitting transducer has DC current in its winding. For the case of supermalloy a magnetization of 100 oersteds is required.

It is not necessary to make the entire delay line from the same material as the radiator (Figure 1). By using a ferromagnetic material for the transducer with a high magnetostrictive constant and by building the delay line out of metal with low damping (for example, Nispan-C), a large delay may be obtained. Nispan-C is a nickel alloy with low damping.

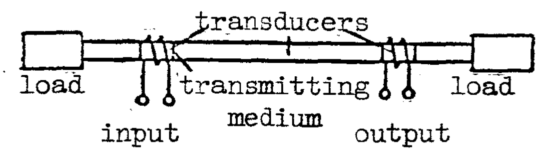

Figure 1

Magnetostrictive transducers make it possible to excite oscillations in a rather large frequency range and their bandpass is rather wide.

Recently, communications have appeared on the development of piezomagnetic transducers which have better performance than piezoelectric or magnetostrictive transducers. Transducers using ferrites operate very well (Ref. 5).

Liquid Delay Lines

The widest application is made of mercury lines with piezoelectric radiators.

To decrease the length of the delay line elbowed construction is used, and the direction of propagation is changed by using reflectors. Each reflector produces an additional attenuation of approximately 3 db. To obtain a greater delay mercury containers with faces are used (Figure 2). Delay lines for several milliseconds have been realized (Ref. 6). The attenuation in mercury delay lines (without reflectors) is 0.0071 db/μsec. Other fluids are seldom used. In water, for example, the attenuation for 1 μsec is 0.129 db. Due to a mismatch in the impedance of the radiator (X-quartz) and the medium, the relative bandpass $\frac{\Delta f}{f}$ is equal to 0.096 for water and 0.89 for mercury.

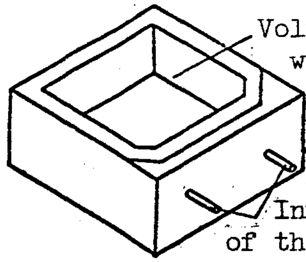

Figure 2

The disadvantage of all liquid delay lines is the cavitation which occurs at high radiated powers (as the frequency increases the maximum allowable power decreases). The attenuation of ultrasonic waves increases substantially at frequencies above 10 Mc so that the dimensions of even the smallest air bubbles or gas bubbles become comparable with the wavelength.

Mercury lines have the following disadvantages: low stability, the temperature coefficient TC is $3 \cdot 10^{-4}$ 1/degree; dangerous and harmful leakage of mercury; and large dimensions for long delays. To decrease the size the diameter is decreased; however, this increases attenuation and may cause mismatching. The necessity of operating with a carrier increases the attenuation:

$$b = k_1 l f^2 + k_2 \frac{1}{d} \sqrt{f} ,$$

where d is the diameter of the container, and k_1 and k_2 are coefficients.

Monolithic Delay Lines /32

Delay lines with piezoelectric excitation most frequently employ fused quartz. The transducers are quartz (X-cut) or barium titanate. Multiple reflection is used to increase the delay time. Frequently, the delay lines have the form of a regular or irregular polygon (Ref. 7). To decrease the size of a delay line it is possible to use three-dimensional systems, and in this case, the quartz must be processed to optical tolerances. Quartz lines which produce a delay of 1200 μsec are known (Ref. 13).

A two-dimensional delay line is shown in Figure 3. If the ratio of the length to the width of the line is p:s, where p and s are mutually simple numbers, the geometric length of the delay line is $l_{delay} = ps\sqrt{2}\,m$, where $m = l_{max}/(pVs)_{max}$.

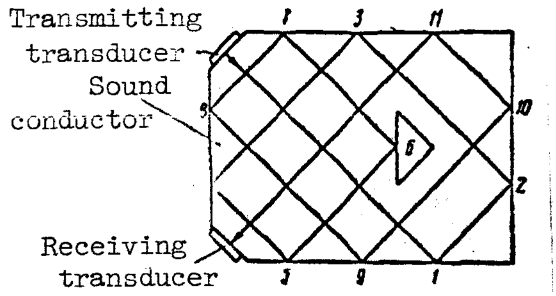

Figure 3

The delay time is $\tau_{delay} = \frac{l_{delay}ps\sqrt{2}}{C_L(pVs)_{max}}$. Let s > p, sm = l_{max} = 5 cm,

τ_d = 64 μsec, $p = \frac{64\cdot 10^{-6}\cdot 5.72\cdot 10^{3}}{0.05\sqrt{2}} \approx 5$. For a three-dimensional delay line for 40 μsec: $psq\sqrt{3}\,m = 2288$; let p < q, s < q, then ps ≈ 1320. Taking the values of q, p, and s to be 39, 38, 37 respectively and specifying l_{max}, we obtain, for l = 10 cm, a distance of greater than 5 mm between reflection points for a wavelength of 0.2 mm (the latter is produced by the necessity of displacing the signal in frequency, f = 30 Mc). The resonance curve is sloped because the losses increase with frequency.

To obtain the long delays it is rational to apply transverse oscillations. When L-waves are incident on a boundary, reflection waves L_1 and S_1 are formed, together with a refracted wave L'. S' does not occur in fluids and gases. In this case we have

$$\frac{\sin\theta_L}{C_L} = \frac{\sin\theta_{L_1}}{C_{L_1}} = \frac{\sin\theta_{L'}}{C_{L'}} = \frac{\sin\theta_{S_1}}{C_S}$$

where θ is the angle of incidence, reflection, and refraction.

Refraction is absent at the boundary between a solid body and gas. The corresponding selection of the angle of incidence for L-waves may reduce the L_1-wave to a minimum. Thus, by using ordinary quartz it is possible to obtain S-waves. When the S-waves are incident at an angle of 45° they are reflected at the same angle and if the boundaries are parallel this angle is retained during all reflections. For multiple reflection the wave trajectory consists of a network of equal density; this is desirable because it makes the reception of ultrasonic oscillations easier and assists in controlling noise (e.g., by the use of absorbers). In the latter case the reflections of the S-waves, by the proper configuration of local boundaries, are transformed into L-waves.

In the general case the network of trajectories may not be rectangular, but this does not produce any complications.

When the geometric dimensions are increased by a factor n, attenuation increases proportionately; the allowable area of the transducer, and consequently the driving power, increase by a factor n^2. Consequently, by properly selecting the dimensions of a delay line it is possible to realize the required level at its output. A simpler method of generating S-waves consists of using a transducer for converting electric oscillations into shear waves. Such a transducer has been produced only in recent years (Ref. 9). It consists of a ceramic transducer of the following composition: 80 percent $BaTiO_3$; 12 percent $PbTiO_3$; 8 percent $CaTiO_3$.

The band of the shear radiator is 1.5 times wider than that of the L-wave transducer. Usually it is necessary to produce a mismatch between the radiator and the load to obtain such a bandpass. Let us compare the performance of delay lines with ceramic and quartz radiators: Δf = 7 Mc, τ_d = 0.707 μsec, b = 40 db and 20-24 db.

The carrier frequency is decreased almost by a factor of 2, which accounts for the sharp drop in attenuation.

To widen the bandpass a half-wave interlayer is used which matches the impedance of the transducer and the medium (Ref. 10). /33

Tape, Cylinder, and Wire Delay Lines

Together with monoliths, various acoustic wave guides are used: rectangular (tape) and round (cylinder, tube). As in the case of radio frequency wave guides, the range of frequencies which is transmitted over the tube is determined by its dimensions and is limited in the region of lower and upper frequencies. Experiments show that cut tubes behave the same way as continuous ones. In connection with this, the transition to tape delay lines is indicated. In these delay lines oscillations of various types may be produced. Oscillations of the O type are without dispersion while the remaining types have dispersion.

The variation of velocity as a function of frequency is shown in Figure 4. The possibility of exciting a certain type of oscillation

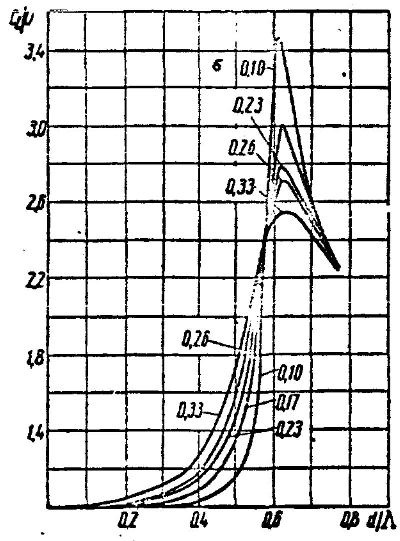

Figure 4

depends on the geometry of the wave guide. The cut-off frequency for the oscillation of the n-th type f_{sp} is determined from the equation $f_{sp} = nf_{s1} = \frac{nC_S}{2a}$, where the second subscript indicates the type of oscillation, while 2a gives the thickness of the tape. Experiments have shown that for torsional oscillations in wire lines the delay of the dispersion is much less than for other types of oscillations (Ref. 12). The advantages of ceramic shear transducers over quartz transducers have been confirmed.

In these delay lines a bandpass of 15-20 Mc and a value of τ_d up to 16.7 milliseconds are achieved (Ref. 15). The problems of attenuation, stability and noise are general for all ultrasonic delay lines.

Attenuation in Ultrasonic Delay Lines

Attenuation is determined by losses in the transducer and in the transmitting medium. Losses in the transmitting medium depend on the purity and structure of the material. All impurities and heterogeneities in the structure of the substance result in an increase of attenuation. In a liquid these impurities consist of dissolved gases, air, etc., while in an amorphous body (e.g., in fused quartz) these impurities consist of fine air bubbles, impurities, heterogeneity in the density. In crystal bodies, coarse structure and impurities increase the attenuation. As the wavelength Λ is decreased the losses increase and when Λ approaches the diameter of the crystals the transmission of the signal ceases. Therefore, an increase in the purity of the transmitting medium and its processing which leads to a decrease in the crystal size (rolling, forging), produces a decrease in attenuation (attenuation is approximately proportional to the dimension of the "grains"). In ferromagnetic materials, losses occur due to overmagnetization which are proportional to the square of the frequency. These (primarily) limit the bandpass. At lower frequencies attenuation increases rapidly at the relaxation frequencies (f_{relax}). The frequency of relaxation for rods of diameters 0.05 mm is shown in Table 2.

Table 2

Material	Invar	Tungsten	Aluminum	Nickel	Iron	Brass
f_{relax} in kc	16.2	16.2	20.8	38	62.7	42

In the delay of a wide band signal, nonmagnetic materials are used exclusively--fused quartz and aluminum alloys.

The second source of losses is the mismatch between the parameters of the transducer and the transmitting medium; however, if ceramic transducers are used instead of quartz, these losses are decreased by approximately 15 db. /34

Temperature Stabilization and Control of Delay Time

When the temperature changes, the delay time also changes due to the variation in the elastic constancy of the medium. Usually the temperature coefficient of the delay (TCD) is 10^{-4} 1/degree (Table 3).

Table 3

Material	Fused Quartz	Mercury	Nickel	Iso-elastic	Nispan-C	6052-6H32
TCD 10^{-4} 1/degree	-1.08	3	1	0.07	1	7

We can see from the table that in order to achieve a stability of $0.4 \cdot 10^{-6}$ (a quarter of an element during one frame) the temperature stability of 0.005-0.05°C is required.

In television τ_d must be rigidly connected with the frequency of the lines. With a delay equal to one line (e.g., in the SECAM system) the allowable nonstability is $2\text{-}8 \cdot 10^{-4}$, i.e., temperature stabilization is not required. However, for a long delay time temperature stabilization becomes necessary, and when the frequency of the lines is unstable the delay time must follow the variations in f_{line}. The following systems and variations in delay time are possible: mechanical systems in which the transducer is displaced with respect to the transmitting medium (these are possible in liquid and magnetostrictive delay lines) or systems in which the geometric length of the delay line is varied by forming it from two wedges (in these cases losses occur at the joints and control is achieved over ±12 μsec.

In another thermomechanical system the transducer is attached to a bimetallic plate whose length is selected in such a way that the variation of τ_d with temperature is compensated by the displacement of the transducer (Ref. 14) (this system may be used for the automatic control of τ_d when f_{line} varies). In another system the dispersion of ultrasonic oscillations is used (in this case the carrier frequency is varied in accordance with the variation of the frequency of lines and in the temperature).

Signal-to-Noise Ratio

In ultrasonic delay lines the oscillations reach the receiving transducer directly and after reflections from the walls of the transmitting medium, as well as from heterogeneities in the medium. In monolithic delay lines there are also reflections which differ from the nominal number. The walls of the transmitting medium are covered with an absorbing material to combat false signals (Figure 5), and the opposite end of the line is capped with an absorbing material and is split, etc. In monolithic lines the sound-absorbing material is applied to the regions on the boundaries from which the signal must not be reflected. In particular, it has been proposed that channels be drilled in the monolith and filled with a sound-absorbing material. The signal-to-noise ratio, depending on the measures which have been taken, is 20-60 db.

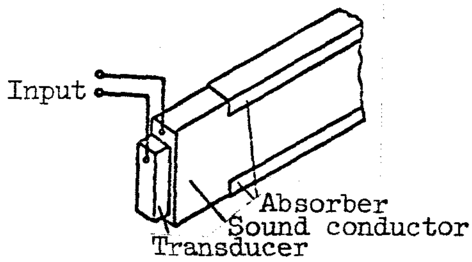

Figure 5

Figure 6 shows the attenuation in a delay line as a function of the product of the delay time and the band $\Delta f \cdot \tau_d$ for mercury lines (curve 1), for monolithic quartz lines with quartz transducers (2 and 2'), for lines with ceramic transducers (3), for lines with torsional oscillations (4), and for magnetostrictive lines (5 and 5'). Furthermore, b(0) corresponds to losses in the transducer, and curves 2', 5' are for the case when the transducer and the line are mismatched to obtain a large bandpass. The points on the curves correspond to various delay lines. From Figure 6 we can see that the attenuation is increased when $\Delta f \tau_d$ is increased; the slope variation is explained by the difference in attenuation for various media and the difference in the bandpass (when $\delta f = \frac{\Delta f}{f_0}$ is small it is necessary to increase the carrier, i.e., to increase the linear attenuation). Quartz lines with ceramic transducers produce the lowest attenuation. The bandpass of magnetostrictive lines and of lines for torsional oscillations is limited by the transducers. However, their valuable /35
properties include their simplicity for medium attenuation and smaller dispersion (in lines with torsional oscillations) which leads us to expect that lines of this type will be designed for greater $\Delta f \tau_d$.

Conclusions

1. At the present time, ultrasonic delay lines make it possible to store television signals for a period of time from one line or less to half a frame (and more). Lines with ceramic shear transducers have the lowest attenuation among the piezoelectric lines.

2. In recent times magnetostrictive delay lines have been brought to the forefront. In a series of cases (for example, in the SECAM system) they may replace piezoelectric delay lines. The development of magnetostrictive lines gives us a basis to assume that they will find a wider

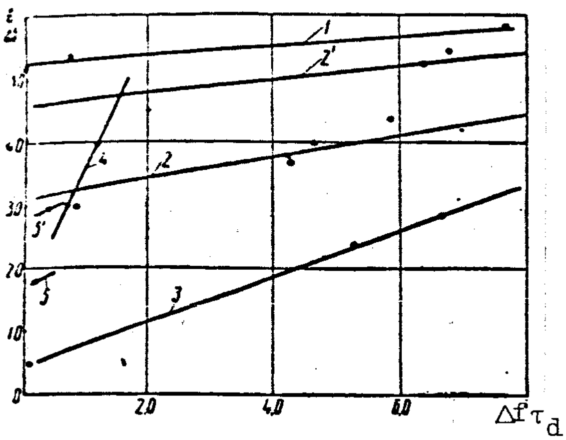

Figure 6

application in television and engineering and the prospects of constructing a delay line for a period of one frame are approaching realization. This will permit the solution of a series of important problems in the development of television engineering.

Moscow Electrotechnical Institute
of Communications

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